AN OFF-THE-SHELF APPROACH TO WINTER CONCRETING

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ABSTRACT

Past studies have demonstrated the feasibility of using chemicals to depress the freezing point of water and to accelerate the hydration rate of cement to allow concrete construction to progress in cold weather. However, little has been done to commercialize this approach to winter concreting, primarily because no acceptance standards have been developed and there are few users who want to be the first to try a new product on their job. Rather than wait for something to happen, this study was initiated to develop an antifreeze admixture that would conform to existing industry standards by using currently available concrete admixtures. The procedure was to evaluate the various commercial admixtures on the market for their effect on freezing point depression and on strength gain at low temperatures. Combining several existing admixtures yielded eight antifreeze formulations that produced the desired antifreeze effect. The admixture combinations allowed fresh concrete to fully cure while its internal temperature was as low as –5°C, yet behave like regular concrete at the time of placement. This project developed the tools to design, mix, place, and cure concrete in below-freezing weather using commercially available off-the-shelf products.

INTRODUCTION

Until recently, no portland cement concrete could be placed in below-freezing weather without thermal protection. That long-held rule just changed. Under FHWA pooled-fund project TPF-5(003) involving 10 state departments of transportation, the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (CRREL), demonstrated the practicality of using commercially available admixtures as antifreeze admixtures for concrete. Admixture formulations from two manufacturers' product lines were developed and evaluated under laboratory conditions for their suitability to field application. In five field trials from New Hampshire to Wisconsin, the admixtures made the concrete easy to work with and gain strength rapidly in winter conditions. The concrete made with these admixtures was able to fully cure at internal temperatures of –5°C, was as durable as normal concrete, and was cost competitive with conventional concreting techniques because no additional heat was required to keep the concrete warm.

This paper reviews the development of an antifreeze concreting technology from the current stock of commercial admixtures and is based on a technical report that details the above-mentioned FHWA study (Korhonen et al. 2004), which ran from October 2000 to October 2003. This paper also discusses efforts to develop an ASTM standard for antifreeze admixtures.

ADMIXTURES

To avoid compatibility problems among admixtures and to limit the possible combinations of admixtures to investigate, this study concentrated on the product lines of two U.S. admixture companies. Table 1 shows eight admixture combinations that were found to be useful for antifreeze concrete made with 392 kg/m^3 cement and water to cement ratios of 0.45 or less. They were developed after numerous trials to yield concrete with the desired –5°C freezing point, reasonable transit life, and good jobsite workability. Of all the commercial admixtures marketed today, these eight combinations are not the only possible antifreeze combinations. Nevertheless, they could serve as the basis for formulating future antifreeze admixture combinations.

Table 1. Eight antifreeze admixture formulations.

Admixture (The admixtures met ASTM C 494 requirements or were otherwise accepted by industry practice.)	**Dosage***			
	Admixture Co. 1			
	I	**II**	**III**	**IV**
Plasticizer, Type A(mL/100 kg)	780	585	390	130
Plasticizer, Type F (mL/100 kg)	195	98	65	390
Accelerating Corrosion Inhibitor (L/m^3)	30	–	30	–
Neutral-Set Corrosion Inhibitor (L/m^3)	–	30	–	30
Accelerator, Type C (mL/100 kg)	6520	6520	6520	5870
Retarder, Type B (mL/100 kg)	–	–	–	260
Shrinkage–Reducing (% cement wt)	–	–	1	–
w/c ratio (target)	0.44	0.45	0.44	0.42
	Admixture Co. 2			
Plasticizer, Type A(mL/100 kg)	780	780	390	780
Plasticizer, Type F (mL/100 kg)	195	195	65	–
Corrosion Inhibitor (L/m^3)	30	30	30	30
Accelerator, Type E (mL/100 kg)	5870	5870	5870	–
Accelerator, Type E (mL/100 kg)	–	–	–	5870
Retarder, Type B (mL/100 kg)	–	65	–	–
Shrinkage–Reducing (% cement wt)	–	–	1	–
w/c ratio (target)	0.43	0.43	0.43	0.39

*The sequencing and timing of when each admixture is dosed into the concrete is critical to the performance of the concrete, both when it is fresh and as it cures. One such dosing sequence is discussed in the *Field Work* section of this paper. No single admixture exceed recommended dosage limits.

LABORATORY WORK

The three primary objectives of combining the Table 1 admixtures into an antifreeze formulation were:

- To depress the freezing point of freshly mixed concrete to at least –5°C.
- To promote strength by antifreeze concrete held at –5°C to develop at least as rapidly as that by control concrete held at +5°C.
- To produce a hardened concrete that is as freeze–thaw durable as control concrete.

Freezing point

Initial freezing points were determined by embedding thermocouples into cylinders (76 × 152 mm) of fresh concrete placed into a –20°C room. The freezing point for each batch of concrete was identified as the location where the slope of the cooling curve began to flatten. At that point, water in the concrete was slightly supercooled. As soon as ice crystals formed, there was a noticeable increase in the temperature (a matter of tenths of a ºC) caused by the release of latent heat of fusion. For the control concrete, ice continued to grow at nearly constant temperature until all water had turned into ice, then the concrete's temperature began to drop again. For the antifreeze concrete, the water did not all freeze at one temperature. This is because the solid that freezes out from a solution is pure ice. As ice developed in the antifreeze concrete, the concentration of admixture in the remaining water increased. Thus, progressively lower temperatures were required to freeze out additional ice. The temperature at which ice first formed was recorded as the freezing point.

A summary of the results obtained for all eight antifreeze formulations is presented in the central column of Table 2. These results represent the target water-cement (w/c) ratios shown in Table 1.

Table 2. Effect of water-cement ratio on freezing point of fresh concrete.

Admixture Combination (by company)		w/c 0.1 Lower than Target		Target w/c ratio		w/c 0.1 Higher than Target	
		Initial Freezing Point (ºC)	**Total % Solids* (by wt of water)**	**Initial Freezing Point (ºC)**	**Total % Solids* (by wt of water)**	**Initial Freezing Point (ºC)**	**Total % Solids* (by wt of water)**
#1	I	–6.3	20.71	–5.5	16.03	–4.5	13.07
	II	–6.1	19.76	–5.2	15.39	–4.4	12.60
	III	–6.7	23.21	–5.8	17.96	–4.5	14.65
	IV	–6.2	20.96	–5.7	15.99	–4.1	12.92
Control		—	—	–1.0**	0.08	—	—
#2	I	–6.9	23.48	–5.2	18.04	–4.0	14.62
	II	–6.9	23.52	–5.2	18.07	–3.9	14.67
	III	–7.2	25.60	–5.3	19.66	–4.0	15.96
	IV	–7.4	23.60	–5.5	17.55	–4.5	13.97

* Equal to the weight of solids in the admixtures dosed into the concrete divided by the weight of free water in the concrete multiplied by 100. ** Korhonen (2002a) shows that w/c ratio has little affect on freezing points of control concrete.

As a guide to the relationship between the concentration of the admixtures in the concrete and their freezing point depression, additional tests were performed at water/cement ratios 0.1 above and below the target value. The results in the right and left of the central columns in Table 2 show the effect that variations in water content have on the initial freezing point of concrete. The relationship between percent total solids and the freezing point can be plotted linearly and used to predict freezing points of different dosages. Alternately, if the freezing point is measured, the percent of solids in the mix can be estimated and used to back-calculate the actual water content of the mix.

Strength development

The purpose of this test was to determine how quickly the concrete would gain compressive strength over a wide range of temperatures. Concrete was mixed at room temperature (25ºC) and cast into 76- × 152-mm plastic cylindrical molds; external vibration consolidated them. All samples were sealed with caps to prevent evaporation and were placed on wire shelves in a curing room 80 to 115 minutes after the mixing water was added. For each mixture, companion dummy cylinders containing thermocouples at their centers of mass were used to monitor temperature history. The samples cooled off rapidly over the first few hours before slowly cooling to their final temperature over the next several hours. For example, samples in a curing room maintained between –4 and –5°C reached –3°C within 6 hours but then took the rest of the day to reach the temperature of the coldroom. However, the –3°C temperature was well below the freezing point of control concrete and it occurred well before the antifreeze concretes reached initial setting. Thus, all strengths reported herein were developed at the temperature of the particular room in which the concrete was cured.

Samples remained in the capped, plastic molds until tested. At various ages, sets of three cylinders were removed from the curing rooms, demolded, and allowed to warm to 5ºC at their center of mass, when necessary. This warming, which took about an hour, ensured that no specimen contained ice during testing, which could incorrectly lead to higher strengths. The cylinders remained in each room until tested or until 28 days. After 28 days, all untested cylinders were moved to room temperature (25ºC) for an additional 28 days of curing. This additional curing showed whether the freezing temperatures had caused any permanent strength loss. Figure 1 shows the results of the best and the worst antifreeze concretes cured at below freezing compared to those of the control concretes cured at two above-freezing temperatures.

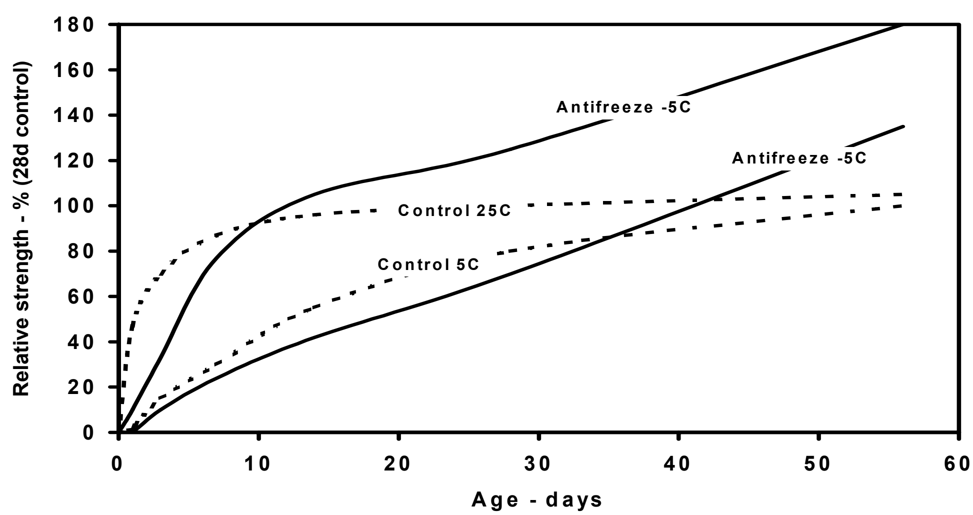

Figure 1. The strength developed by the best- and worst-performing antifreeze concretes cured at –5°C compared to control concretes cured at 25 and 5°C (based on ACI (1988) data). As can be seen, even the poorest performance of an antifreeze concrete nearly equaled that of control concrete at 5°C at early age and outperformed the control at late age.

Another laboratory test was performed to determine if the antifreeze concrete provided additional protection from freezing damage below the design temperature of –5ºC. The goal was to determine how much maturity (strength) the concrete needed to gain before it could survive temperatures below –5°C. A representative antifreeze concrete was mixed at room temperature, cast into cylinders, and, 30 minutes after water, cement, and admixtures were combined, placed in –5, –10, and –20ºC rooms. At 2-hour intervals thereafter, additional samples were placed into each of the three coldrooms. After curing for 24 hours, each set of three was removed from the coldroom and allowed to cure at room temperature an additional 7 days. At that time the samples were tested for compressive strength. The results were compared to samples continuously cured at 28°C for 7 days.

The results of this test are presented in Figure 2. As expected, the samples placed into the coldrooms ½ hour after mixing showed no damage when held at the –5ºC condition for 24 hours. However, at –10 and –20ºC, they did not recover fully; in fact, they developed only 60 to 65% of their strength relative to the samples cured at room temperature. The remaining groups of samples—held 2½, 4½, and 6½ hours at room temperature before being placed into the cold rooms—showed no reduction in strength for any of the three freezing temperatures. Interestingly, the 2½ hour samples had developed no measurable compressive strength before they were placed into the coldrooms. Thus, one can expect the antifreeze concretes in this study to be able to resist an overnight freeze of at least –20°C, provided they are pre-cured for an equivalent of 2½ hours at room temperature, which correlates to 90°C-hr of maturity (Nurse-Saul method with –7°C datum).

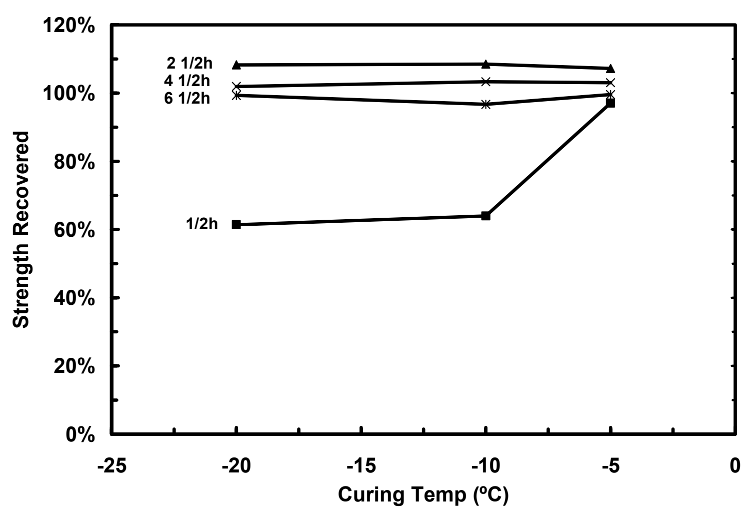

Figure 2. Effect on strength recovery by subjecting early age antifreeze concrete to various low temperatures for 24 hours, then to room temperature for 7 days, compared with the strength developed in concrete samples continuously cured at room temperature for 7 days.

Freeze–thaw durability

Freeze–thaw durability tests were conducted as part of the performance tests on concrete made with the candidate antifreeze admixtures. The objective was to verify that the admixtures did not harm the freeze–thaw durability of concrete.

Testing was conducted using ASTM C 666, Procedure B. Sample results from the durability tests are presented in Figure 3. As can be seen, when the concrete is non-air-entrained, both antifreeze and control concrete exhibit essentially the same resistance to repeated cycles of freezing and thawing. This illustrates that the chemicals do not prematurely degrade freeze–thaw durability. When the concrete was entrained with air, the results were mixed. As Figure 3 shows, the results for air-entrained antifreeze concrete ranged from being unaffected by the test to acting as if it was non-air-entrained. At first, this was both puzzling and a concern. However, it was later determined that some of the beams had probably lost a good portion of their entrained air during their fabrication process, because the admixtures tended to detrain air. In a separate study, we measured the air contents of freshly mixed antifreeze concrete over time and found that the air content of freshly mixed antifreeze concrete could drop from 9 to 3% within 45 minutes if the concrete was worked too much. Subsequent tests on other samples of hardened antifreeze concrete showed that air bubbles could be present in sufficient volume and in appropriate distribution. These results, though they show that that antifreeze concrete can be entrained with air, convinced us that trial batches should be made to verify that proper air content could be maintained in a particular mix design before it could be used in the field. During field tests air contents met expectations.

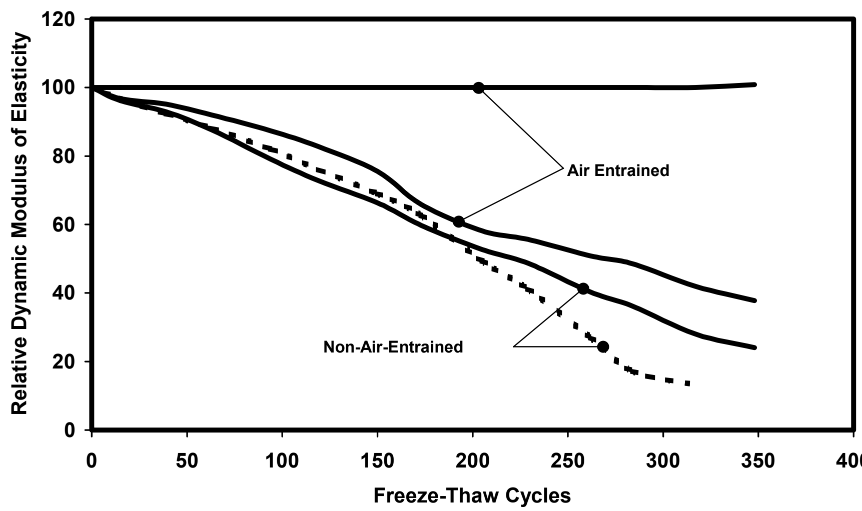

Figure 3. Freeze–thaw results. Solid lines are from antifreeze concrete while the dotted line is from control concrete. The two air-entrained results are from the best and the worst performances received from all the antifreeze tests. These two results illustrate that obtaining proper air contents in antifreeze concrete was sometimes a challenge. (Air-entrained control concrete [not shown] behaved exactly like the "best" line for the air-entrained antifreeze concrete.)

FIELD WORK IN WEST LEBANON, NH

A critical part of this study was to achieve the reliable use of antifreeze concrete in the field. This required assurance that the antifreeze formulations worked for full size batches under actual construction conditions in subfreezing weather. Five full-scale field projects were conducted; the results from one of those studies follow.

New concrete curbing and two abutments were repaired on the west side of the Trues Brook Bridge on NH Route 12A about 5 km south of West Lebanon, NH. The repair used two truckloads of concrete (formulation IV using company 2 admixtures, Table 1) and was carried out on 18 Dec 2002. The bridge carries about 5000 vehicles per day.

The repair section

The curbing, running north and south along the west side of the bridge, measured approximately 460 mm wide by 380 mm deep by 32 m long. It contained steel reinforcing bars, with anchor bolts for the guardrail welded to the bars (Fig. 4). The abutment repairs, on both the north and south ends of the curbing, measured 380 mm wide by 230 mm deep by 2 m long, and sloped away from the bridge at a 46% grade.

Figure 4. Trues Brook Bridge curb ready for repair.

Batching the concrete

The ready-mix plant was located about 1.5 km north of the bridge. The first truck was loaded with the first admixture at about 9:45 a.m. and then with enough cement (392 kg/m^3, Type I/II), sand, coarse aggregate, air-entrainer, plasticizer, and cold water to make 3.5 m^3 of concrete with a w/c ratio of 0.25 (excluding the water fraction of the admixture already in the truck). The drum was turned at mixing speed for 3 minutes and stopped before the second part of the antifreeze mixture was pumped into the drum at 10:05 a.m. The second admixture, unlike in previous tests where immediate mixing occurred, remained unmixed within the truck until it arrived at the bridge at 10:15 a.m. The mixing was delayed until the truck arrived at the jobsite to avoid slump loss that was likely to occur during transit, as the second admixture was an accelerator. It worked! Once the concrete was mixed for 3 minutes, it came out of the truck with a full 200 mm slump and a w/c ratio of 0.37 (the control mix, the basis for this mix, had a 0.44 w/c ratio). Normally, we design the mix to start out at the ready-mix plant with a high slump (200–230 mm) so that by the time it gets to the jobsite it still retains reasonable workability (100-mm slump). By delaying the final mixing time, we essentially created a zero-delivery-time concrete. This has interesting implications for reducing admixture dosing rates and costs. Once the concrete was mixed, it was discharged into the forms.

The identical mixing process occurred with the second truckload, producing the same results (except that a few balls of dry, unmixed concrete came out at the beginning of the pour). Because the plant was so close to the jobsite, there was no concern about creating a cold joint between the two consecutive placements. Consequently, the second truck was not batched until the first truck had completely discharged its load. In retrospect, the second truck could have waited onsite for a while behind the first truck without affecting the concrete on board because of the delayed mixing process.

<u>Placing the concrete</u>

Concrete placement from the first truck began at 10:25 a.m. A sample of concrete was obtained in a wheelbarrow at 10:30 a.m. Soon after that, the fresh concrete was measured to have a temperature of 10^{o}C, an air content of 11.1% (high), a unit weight of 2240 kg/m^3, and a slump of 200 mm (target value). Three 51- by 102-mm sample cylinders were also obtained and measured for a freezing point of –6.6^{o}C. Numerous 76- by 152-mm concrete cylinders were also fabricated for later strength testing. The strength cylinders were used to estimate the strength gain of the concrete in the bridge using the maturity method.

The concrete was placed on the northern abutment first. It was held in place on the slope by a piece of plywood nailed to the top of the sidewall forms. Because the concrete was expected to stiffen rapidly, the piece of plywood was removed 15 minutes after the concrete was placed. This allowed the soft surface of the concrete to be finished, while avoiding any tendency for it to slide down slope. The truck discharged the last of its concrete at 10:45 a.m.

The second truck arrived at 11:05 a.m., mixed for 3 minutes, and began placing the concrete at approximately 11:15 a.m. At 11:20 a.m. a wheelbarrow was filled with concrete from which measurements of the fresh concrete properties were made. The freezing point was measured to be –6.5^{o}C, the slump was 180 mm, the air content was 10.4% (we lowered the AEA dose for this truck but the air content was still too high), the unit weight was 2280 kg/m^3, and the mix temperature was 11^{o}C. The final concrete was placed at 11:27 a.m.

Because the second truck was expected to contain some concrete at the end of the job, and it was likely to stiffen inside the drum if it remained there too long, a place was prepared to discharge the waste concrete and wash water.

The work of placing the concrete, not including the waiting time between the two trucks, took 31 minutes, between 10:25 a.m. and 11:27 a.m. Emplacement consisted of directing the concrete with the truck's chute, consolidating it with an internal vibrator

(Fig. 5), and finishing the resulting surface with a magnesium float. No further work was done to the concrete. At approximately 1:00 p.m., the finished concrete was covered with a sheet of plastic (to minimize evaporation) and with a 25 mm-thick insulation blanket. The insulation was not needed to protect the mass of the concrete against freezing, but to prevent localized freezing where steel bolts protruded from the finished surface. Air temperatures were expected to drop significantly below the freezing point of the concrete. And they did! (Fig. 6)

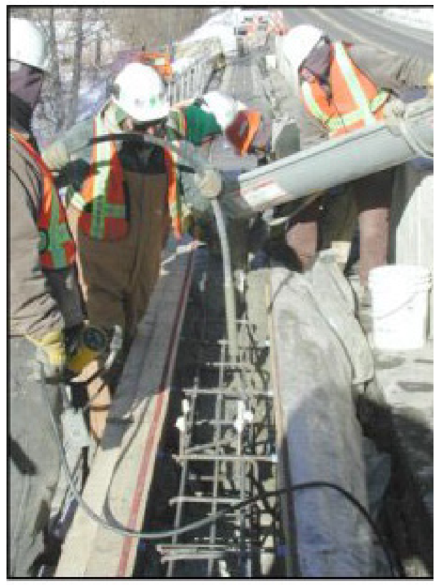

Figure 5. Placing and consolidating the concrete.

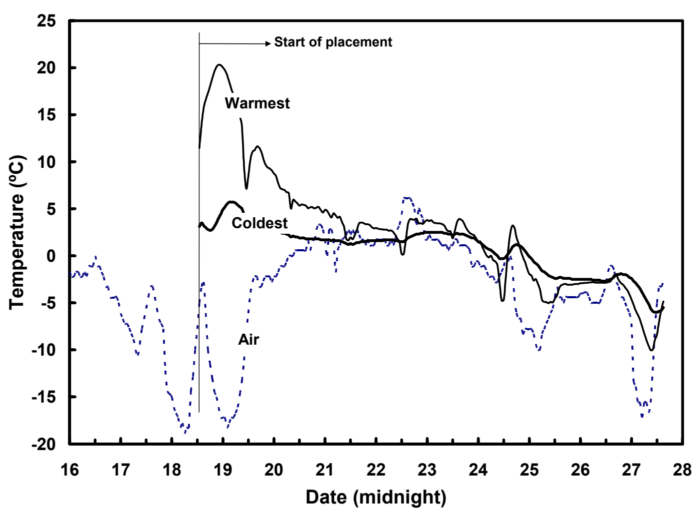

Figure 6. Temperatures of the air and two locations within the curbing.

<u>Strength development</u>

To estimate strength development at various points in the bridge concrete, we tested samples for compressive strength at various ages from the samples cast during placement. Seventeen cylinders were stored in picnic coolers next to the bridge, with two of them containing embedded thermocouples to monitor temperature history. Sets of three samples were periodically transported to the CRREL laboratory for testing. Another 26 cylinders were immediately returned to CRREL after the placement and stored in a 23°C room, with two of these cylinders similarly instrumented with thermocouples. All specimens remained in their plastic molds until tested. A maturity curve was developed from the strength data for samples stored in the picnic coolers, cylinders cured in the lab, and temperature data obtained from the dummy cylinders at both locations. Once the maturity curve was developed, the curbing's strength could be estimated for any thermocouple location in the bridge using its temperature-time history.

The strengths developed at two points in the curbing are shown in Figure 7. The warmest portion of the curb, the top surface beneath the insulation, reached 20 MPa in less than 3 days. The coolest portion of the curb, that in contact with the existing concrete substrate, reached 20 MPa in approximately 5 days. The forms were removed from the concrete on the fifth day. Figure 6 shows the temperature of the outdoor air and the two points that relate to Figure 7.

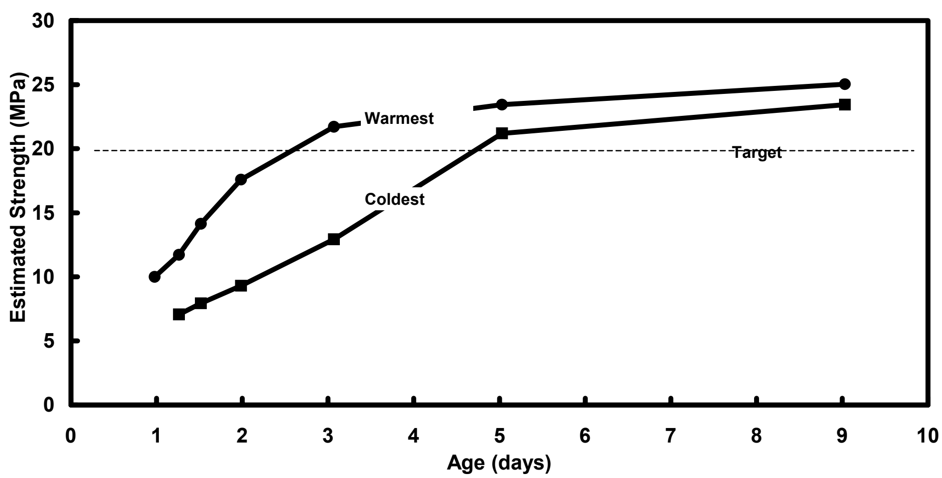

Figure 7. Strength gain curves for two critical points in the curbing.

<u>Costs</u>

The primary difference between normal winter concreting practice and that of using antifreeze concrete is the heat, shelter, and labor needed to protect normal concrete compared to the chemicals needed to protect antifreeze concrete. The bridge curbing replacement in West Lebanon, NH, provided an opportunity to directly compare the antifreeze method to a method that used a heated shelter to repair the curbing on the opposite side of the bridge. Specifically, the shelter required 132 labor-hours to erect and dismantle, it consumed about \$100 in materials, and it cost \$750 to heat. For the antifreeze concrete, on the other hand, the only extra cost was that of the admixtures themselves (\$700). It took 1 hour to place 6 m^3 of antifreeze concrete outdoors, but 3 hours to place the same quantity of normal concrete inside the shelter. Clearly, the antifreeze method proved to be faster and less expensive than the conventional winter concreting method.

ACCEPTANCE STANDARD

Korhonen (2002b) reported on a Civil Engineering Research Foundation effort that started in 2000 to develop a report of what later would become the basis for work on an acceptance standard for antifreeze admixtures. In June 2003, a draft standard for low temperature admixtures, based on the CERF report, passed the balloting of ASTM subcommittee C09.23, Chemical Admixtures. This signaled that there was sufficient interest to proceed with the standard, and section C09.23.05, Cold Weather Admixture Systems, was subsequently formed. In December 2003, a second draft of the proposed standard was reviewed and a plan was devised in which four U.S. admixture companies would conduct laboratory investigations to verify that most commercial laboratories could meet the testing requirements of the proposed standard. June 2004 is the scheduled date for the second meeting of the newly formed ASTM section. By that time it is hoped that all questions will have been answered and that a final standard can be forwarded for committee balloting.

CONCLUSIONS

The formulation of antifreeze admixtures from commercial off-the-shelf admixtures is an effective technology. In laboratory tests, up to eight admixture formulations were shown to be effective at depressing the freezing point of fresh concrete below –5°C, at promoting reasonably rapid strength development in concrete cast in cold weather, and at producing a freeze–thaw durable concrete. In field studies, the admixture formulations developed in the laboratory allowed concrete to be mixed, placed, finished, and cured at air temperatures that dipped as low as nearly –20°C. The field studies showed that this antifreeze technology was faster and less expensive than conventional cold weather concreting practice. Finally, the development of an ASTM antifreeze admixture standard, which is currently underway, should help open the market to the manufacture of newer, more efficient antifreeze technology. And, the fact that 10 state departments of transportation sponsored this study suggests that there is a market for antifreeze technology.

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